Towards an extragalactic supernova neutrino detector at the South Pole

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Neutrinos from extragalactic core-collapse supernovae (SNe)

- With today's neutrino observatories, only Galactic SNe (~2–3 per century) visible[1]
- Need to extend sensitivity to neighboring galaxies (5–10 Mpc) for a routine detection of ~1 SN per year in neutrinos (see Figure 1), this means ~10 Mton detector needed (see below)
- Physics motivation:
  - Measure the core-collapse SN rate accurately
  - Study the core-collapse mechanism
  - Trigger early optical observations of SNe
  - Probe for optically dark SNe (see below)
  - Set limits on neutrino mass

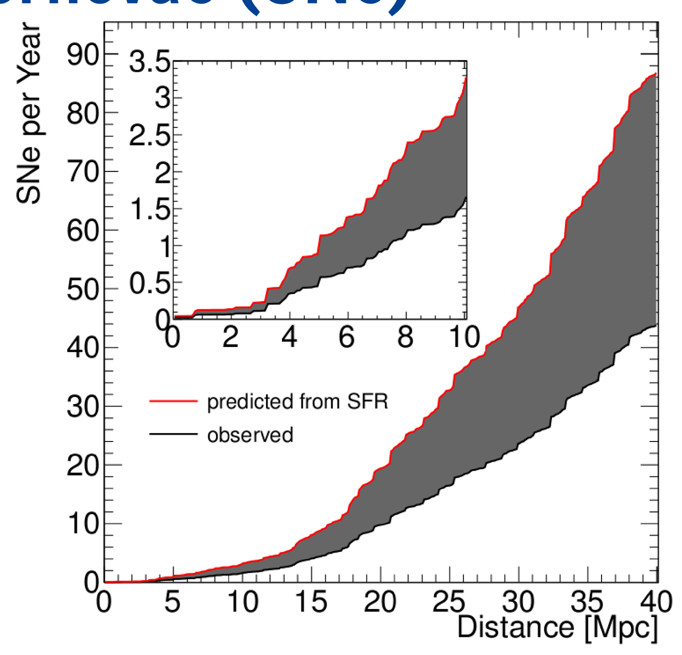


Fig. 1: Cumulative number of SNe per year, as predicted from star formation rate (red)[2,5] and as observed (black)[2,3,4]

Simulation setup

- Studied two locations for Cherenkov array in South Pole ice: shallow **diffuse ice** and deep **clear ice**

Ice properties:[10,11] Clear ice has low scattering, diffuse ice "captures" photons

Ice type	Depth	Absorption Length	Scattering Length
diffuse	750-1050 m	350 m	0.3 m
clear	2150-2450 m	20-90 m	20-50 m

- Strings arranged in hexagonal pattern
- 300 optical sensors on each string (1 sensor per meter), each having an eff. photosensitive area:
  - ~78 cm² in diffuse ice (2.4 high QE IceCube sensors)
  - ~180 cm² in clear ice (5.5 high QE IceCube sensors)
- Photon propagation:
  - diffuse ice: random walk
  - clear ice: Photonics[9]
- Event trigger requirement: 5 photon hits anywhere in detector
- SN trigger requirement: ≥ 3 (10) ν events within 1–10 s

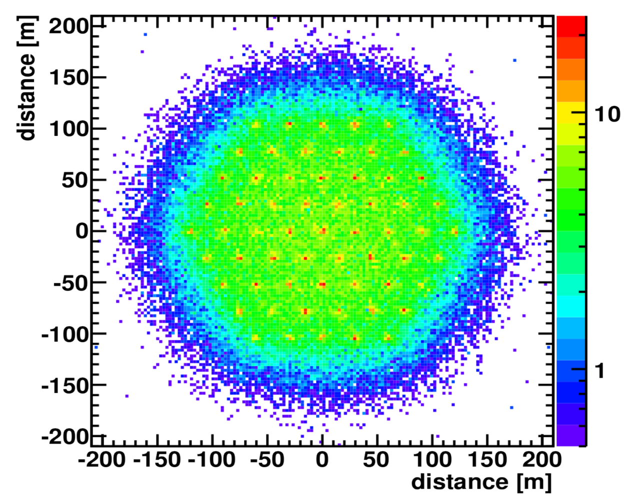


Fig. 3: Detector viewed from above (# of detected photons as function of neutrino vertex position)

Supernova models

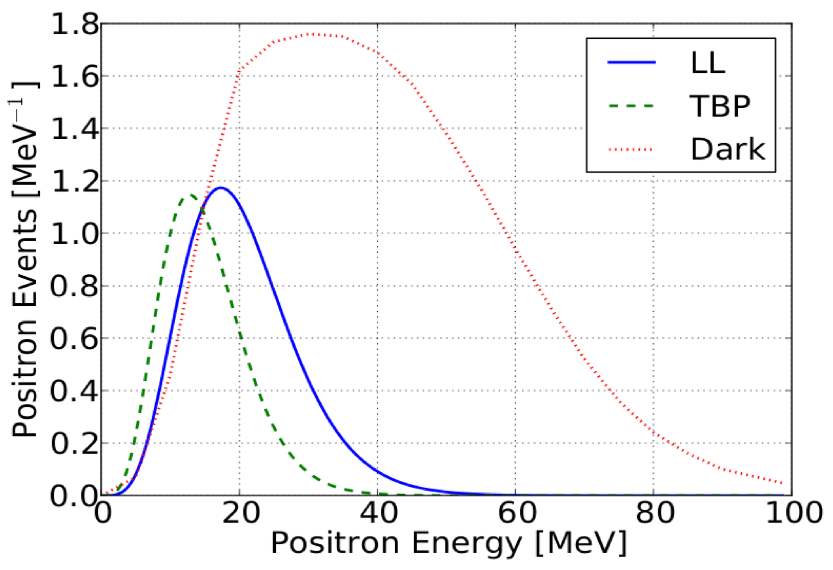


Fig. 2: Positron spectrum from SN in 1 Mpc distance for 1 Mton effective mass

These models of SN neutrinos were used:

- **Lawrence-Livermore model[6] (LL):** One of the few model calculations leading to an explosion
- **Thompson-Burrows-Pinto model[7] (TBP):** More recent than LL, but does not lead to an explosion.
- **Dark SNe[8]:** While the collapse of a fast-rotating star with ≳ 25 M⊙ leads to a hypernova, a slow-rotating one might collapse to a black hole without emitting photons. These „dark" SNe or failed SNe could be detected with a SN ν detector.

Geometry optimization

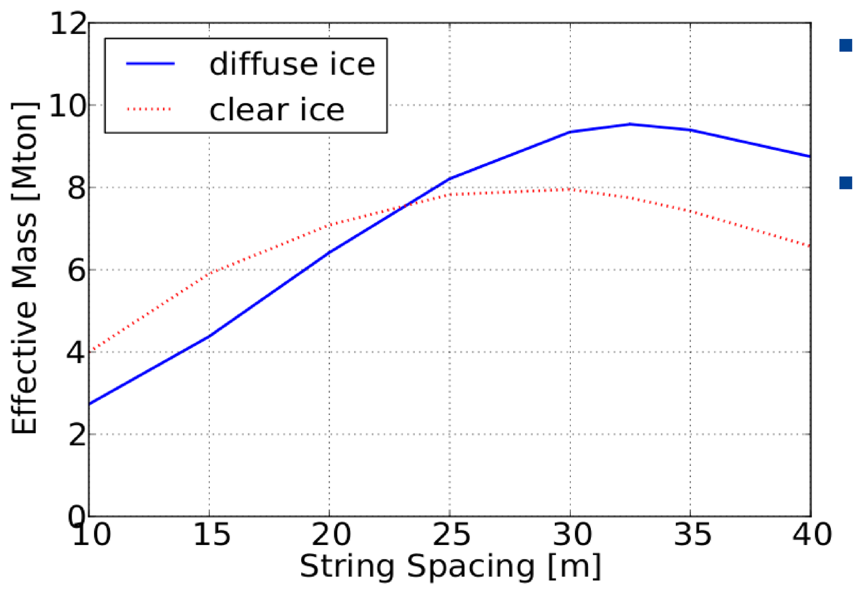


Fig. 4: Effective mass at trigger level for positrons from LL spectrum (61 strings)

- Starting point: 61 strings
- **Diffuse ice:** high photon detection prob. due to weak abs. and strong scatt. (solid curve)
- But photon scattering prohibits directional reconstructions and discrimination of noise → diffuse ice no option
- **Clear ice:** scaling sensors' photosensitive area up by factor 2.3 (i.e. ~180 cm² per sensor), similar performance is obtained (dotted curve)

Backgrounds

Backgrounds are challenging, need BG rate ≤4 mHz to get at most 1 fake SN event/year

- **Atmospheric muons[12]**: Easily recognized if through-going. Need outer veto layers (IceCube) against stopping muons. Diffuse ice: 14% dead time, clear ice: 0.16% dead time
- **Solar neutrinos[13]**: Only ν_e that cannot interact via inverse beta decay (IBD), thus elastic scattering on electrons (lower x-sec than IBD).[14] Can discriminate via energy and direction (latter only in clear ice)

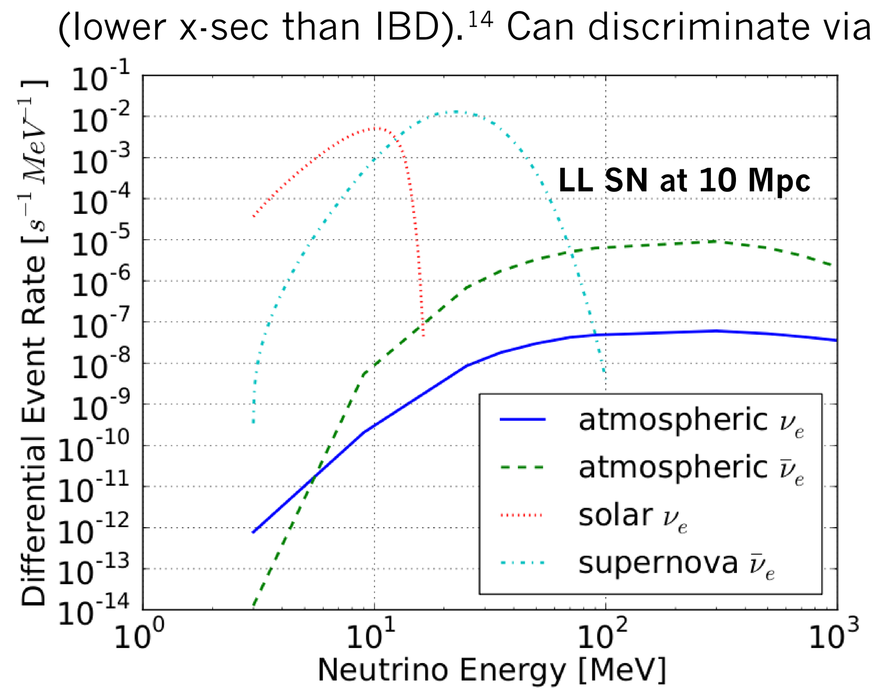


Fig. 6: Differential event rate (clear ice, 127 strings)

Rates for 127 strings after noise cuts:

Rate [mHz]	Trigger 5 phot.	Trigger 7 phot.
Solar ν_e	28.2	7.9
Atm. ν_e	0.32	0.27
SN Signal	100%	63%
Michel e⁻ (atm. ν_μ)	~1.5 mHz*	

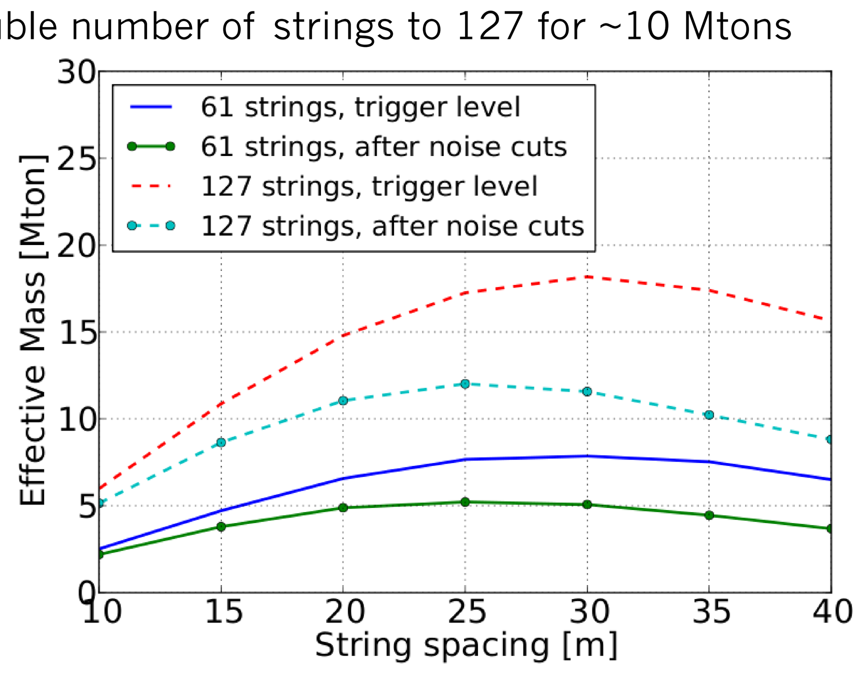
* = SuperK measurement[16] scaled up

- **Atmospheric neutrinos[15]:** ν_e component small, ν_μ contrib. via invis. μ (under Cherenkov thresh.) that decay to visible Michel electrons
- **Sensor noise**: Needs to be low (few Hz). Temporal and spatial pattern of signal must be exploited for discrimination of noise, impossible in diffuse ice

Noise cuts

- Reject events triggered by sensor noise using hit topology
- Eff. mass significantly reduced, low noise rate is crucial!
- Need to ~double number of strings to 127 for ~10 Mtons

Fig. 5: Effective mass before and after noise cuts for 61 and 127 strings in clear ice (10 Hz noise per optical sensor)



Results SN detection rate and detector reach

- SN detection probability computed from eff. mass in clear ice (~5 Mtons for 61 strings, ~12 Mtons for 127 strings); see Fig. 7
- Using Fig. 7 and Fig. 1, taking observed as lower and predicted SN rate as upper limit, we estimate the **number of SN detections per year**:

61 strings (clear ice):

Model	Nν ≥ 3	Nν ≥ 10
LL	1.0 – 2.0	0.2 – 0.4
TBP	0.5 – 1.0	0.1 – 0.2
Dark SN*	0.9	0.1

127 strings (clear ice):

Model	Nν ≥ 3	Nν ≥ 10
LL	2.3 – 4.6	0.5 – 1.1
TBP	1.1 – 2.2	0.3 – 0.5
Dark SN*	2.0	0.3

* = assuming dark SNe occur at 10% of observed SN rate

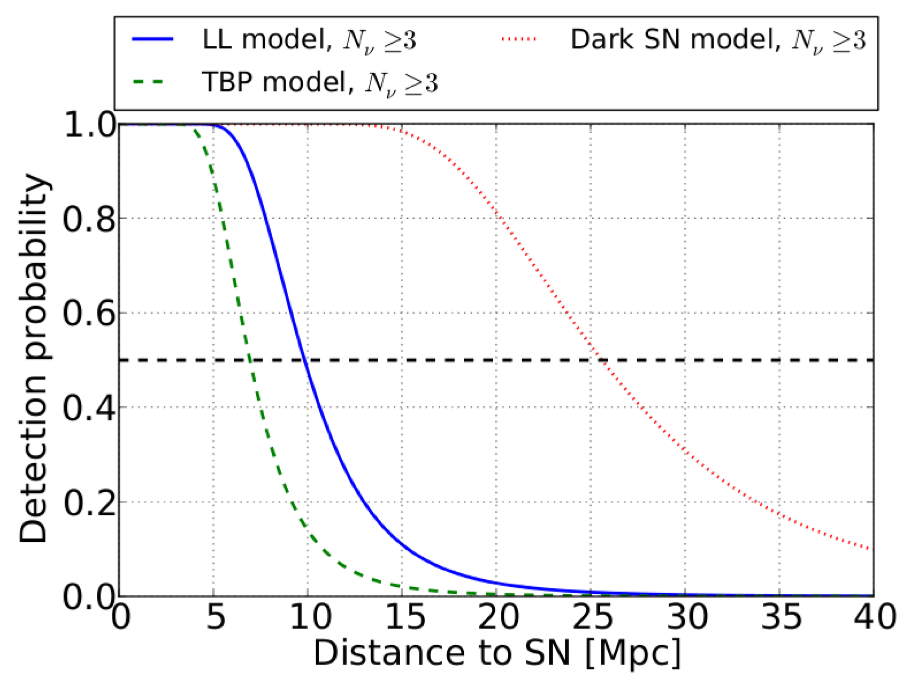


Fig. 7: SN detection probability as function of SN distance (clear ice, 127 strings, noise cuts applied)

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